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Reflection-type photoplethysmography pulse sensor based on an integrated optoelectronic chip with a ring structure

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Abstract: Reflection-type photoplethysmography (PPG) pulse sensors are widely used in consumer markets to measure cardiovascular signals. Different from off-chip package solutions in which the light-emitting diode (LED) and photodetector (PD) are in separate chips, a GaN integrated optoelectronic chip with a novel ring structure is proposed to realize a PPG pulse sensor. The integrated optoelectronic chip consists of two multiple-quantum well (MQW) diodes. For higher sensitivities, the central and peripheral MQW diodes are suitable as the LED and PD, respectively. The results indicate that the integrated optoelectronic chip based on a blue LED epitaxial wafer is more suitable for the integrated PPG sensor based on device performance. Moreover, the amplitude of the PPG pulse signal collected from fingertips is higher than that from a wrist. The feasibility of the reflection-type PPG pulse sensor based on a GaN integrated optoelectronic chip is fully verified with the advantages of smaller sizes and lower costs.

1. Introduction

Cardiovascular signals such as blood flow changes or heart rates can provide valuable information for patient diagnosis in clinical applications, the daily health nursing of elders and people with heart problems, and continuous sports health monitoring [1–3]. The reflection-type photoplethysmography (PPG) pulse sensors [4–8] feature noninvasive measurements, low costs, fast response, simple structure, and convenient test methods and are preferred to obtain cardiovascular signals in consumer markets. A basic PPG sensor only requires a light emitter to illuminate skin tissue and a photodetector (PD) to detect small variations in the light intensity associated with blood volume changes in the microvascular bed. Compared with the transmission-type PPG sensor that uses infrared light sources [9–11], the reflection-type that generally uses a green light source can be placed on various parts of human skin to detect reflected light and is less susceptible to interference from thermal stress [11]. A shorter distance between the light emitter and PD helps improve the reflected light ratio and resulting device performance. Thus, Chen et al. recently developed a PPG pulse sensor based on an integrated optoelectronic chip [12] in which the LED and PD are on a single chip and the sapphire substrate can directly contact the skin. The distance between the LED and PD can reach micron scales, which cannot be achieved from existing off-chip packages. Furthermore, much lower cost and more efficient packages are expected for the integrated optoelectronic chip with an LED and PD as realized by the same epitaxial layers and fabrication process. However, many issues need to be solved for the practical application of this PPG sensor based on an integrated optoelectronic chip. First, unlike off-chip packages in which the light emitter and PD are independently selected, the performances of the LED and PD in the integrated optoelectronic chip are simultaneously restricted by the parameters

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of InGaN/GaN multi-quantum well (MQW) diodes [13–16]. Therefore, the green light usually adopted by off-chip package schemes may not be suitable for integrated PPG sensors, indicating LED epitaxial wafers of suitable wavelengths should be identified. Second, novel structures for the integrated optoelectronic chip are anticipated to better meet the needs of reflection-type PPG sensors. Third, a complete PPG pulse sensor prototype based on an integrated optoelectronic chip, which has not been demonstrated to date, needs to be developed to validate the feasibility of practical applications. To solve the above issues, this paper builds a PPG pulse sensor system that includes an integrated optoelectronic chip with a novel ring structure, a week signal processing circuit, signal analysis and display unit. Moreover, integrated optoelectronic chips with blue and green emission spectra are compared to determine the suitable wavelength for the integrated reflection-type PPG sensor.

2. Design and fabrication

The integrated optoelectronic chips are implemented on 4-inch commercial GaN-on-sapphire LED epitaxial wafers. The epitaxial layers on the sapphire substrate are an AlN buffer layer, an unintentional-doped GaN layer, an N-doped GaN layer, an InGaN/GaN MQW layer, and a p-GaN layer, from bottom to top. The fabrication processes of the integrated optoelectronic chip are similar to common discrete flip-chip LEDs [17]. The details are illustrated in Fig. 1 and described as follows. First, as shown in Fig. 1(a), a transparent indium tin oxide (ITO) current spreading layer is deposited via sputtering and treated using rapid thermal annealing in an N_2 atmosphere for 7 min. Second, as shown in Fig. 1(b), the mesa regions are defined by photolithography and etched to the N-doped GaN layer by inductively coupled plasma reactive ion etching (ICP-RIE). Third, as shown in Fig. 1(c), a deep ICP-RIE is further performed to etch all epilayers for device isolation. Fourth, as shown in Fig. 1(d), the Ni/Al/Ti/Al multi-layers are evaporated via electron beam evaporation (EBE) and lifted off to form the p-contact metal. Fifth, as shown in Fig. 1(e), a 1 µm-thick SiO_2 is deposited by plasma-enhanced chemical vapor deposition (PECVD) and

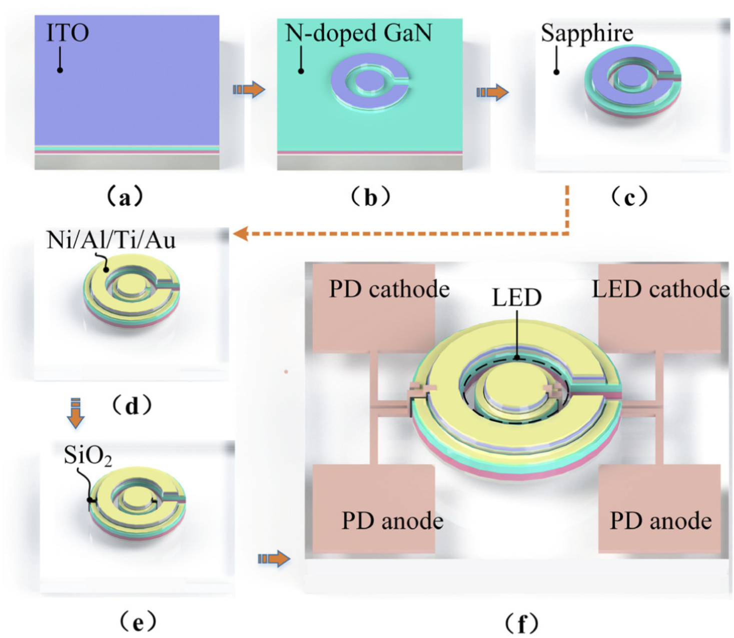

Fig. 1. Fabrication processes of the chip used for the reflection-type PPG pulse sensor.

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patterned to realize electrical isolation. Sixth, as shown in Fig. 1(f), the Ni/Al/Ti/Pt/Ti/Pt/Au multi-layers are evaporated by EBE and lifted off to form the large-sized electrode for flip-chip packing. The sapphire substrate is thinned to 200 µm to improve the light extraction from the sapphire side.

Figure 2 shows the final structure of the integrated optoelectronic chip sized at 2.6 × 2.6 mm after ultraviolet nanosecond laser dicing. The LED and PD have identical epitaxial layer structures (MQW diode) but are in different shapes. The center MQW diode is adopted as the LED and the peripheral is the PD in our design. Two MQW diodes are separated using a deep isolation trench, and the patterned substrate is observed in Fig. 2. The patterned sapphire substrate can effectively reduce the dislocation density of epitaxial layers to improve the luminous efficiency of the MQW diode [18].

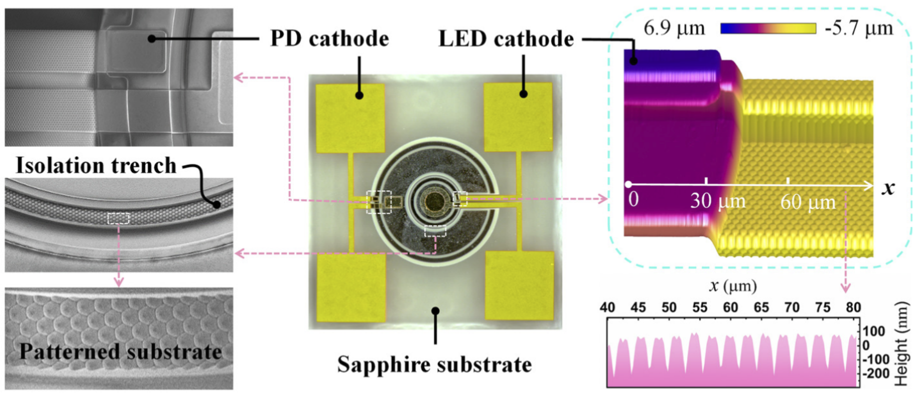

Fig. 2. Images of the integrated optoelectronic chip

3. Measurement results

The performance of two integrated optoelectronic chips based on blue and green LED epitaxial wafers are characterized to determine the suitable chip for the PPG pulse sensor system. For measurement convenience, the integrated optoelectronic chips are flip-chip bonded to a flexible printed circuit board and encapsulated in polydimethylsiloxane (PDMS) strips, as shown in the insets of Fig. 3. Figure 3(a) shows the IV characteristics of the PD based on the blue epitaxial wafer, in which different currents are injected into the adjacent LED. For the IV curves in the lower left of Fig. 3(a), the central MQW diode is used as the LED and the peripheral is the PD. For the IV curves in the lower right of Fig. 3(a), the central MQW diode is used as the PD and the peripheral is the LED. The contrast shows that the peripheral MQW diode is more suitable for the PD of the PPG due to the higher output current. The reason for this phenomenon is that the light emitting from the central MQW diode is more easily collected by the large-sized peripheral MQW diode. The IV characteristics of the PD based on the green epitaxial wafer shown in Fig. 3(b) present the same contrast. Comparing the results in Figs. 3(a) and 3(b) indicates the PD of the integrated optoelectronic chip based on the blue epitaxial wafer has a larger photocurrent. To explain this phenomenon, the electroluminescence (EL) spectra and response spectra (RS) of the MQW diodes based on blue and green LED epitaxial wafers are measured. As seen in Fig. 4, the overlapping wavelengths of the EL spectra and RS for the blue MQW diode are significantly larger than those of the green MQW diode. Therefore, the integrated optoelectronic chip based on the blue LED epitaxial wafer is more suitable for the integrated PPG sensor based on the device performance.

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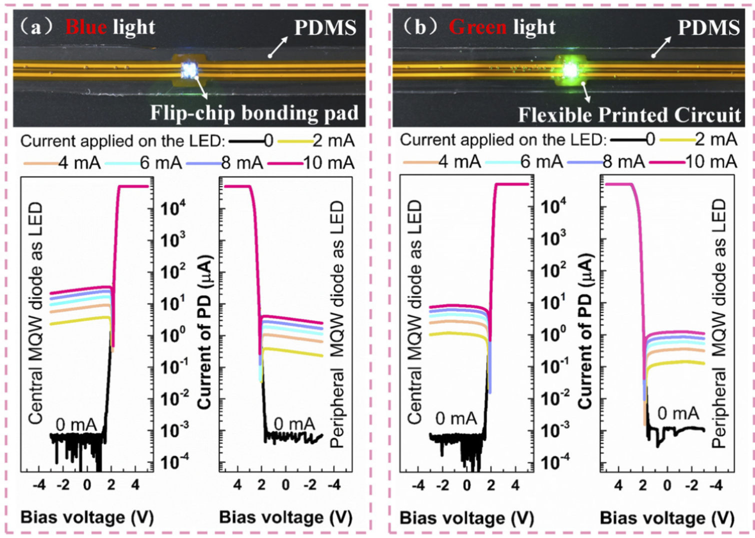

Fig. 3. (a) Packaged integrated optoelectronic chip and IV characteristics of the PD based on the blue epitaxial wafer, (b) packaged integrated optoelectronic chip and IV characteristics of the PD based on the green epitaxial wafer.

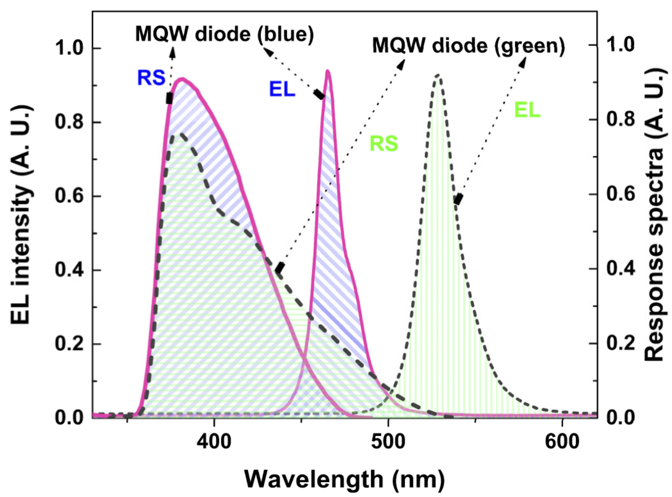

Fig. 4. EL spectra and RS of the MQW diodes based on blue and green LED epitaxial wafers.

The simple test platform shown in the inset of Fig. 5 is built to verify the PD's ability to detect reflected light emitting from the LED. The PD photocurrent on the integrated optoelectronic chip is caused primarily by the light emitted directly from the LED and only a small part is caused by light from the reflector. The results shown in Fig. 5 indicate that the PD photocurrent caused by reflected light decreases significantly with the distance between the integrated optoelectronic chip and the reflector. Therefore, for practical applications of the reflection-type PPG pulse sensor, the distance between the chip and human skin should be as small as possible. The corresponding solutions are to place the sapphire substrate of the chip directly on the skin and reduce the sapphire thickness.

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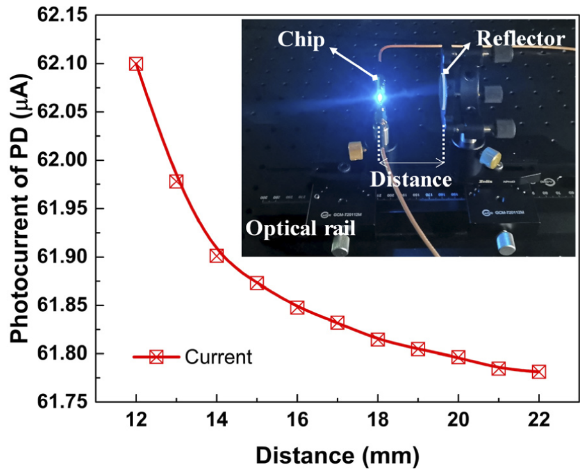

Fig. 5. Photocurrent of PD with respect to the distance between the integrated optoelectronic chip and reflector.

The test platform shown in Fig. 6 is built and an external LED is used as the modulation light source to verify the PD's ability to detect external modulated optical signals that simulate heart pulses. The pseudo random binary sequence (PRBS) data applied to the external light source is generated with a Keysight 33600A series waveform generator. The central MQW diode is used as the PD and the peripheral is the LED from the integrated optoelectronic chip based on the blue LED epitaxial wafer. The measured voltages of the PD with a 1 MΩ oscilloscope under incident PRBS data of 100, 200, and 500 bps are shown in Figs. 6(b), 6(c), and 6(d), respectively. In each case, the measured voltages of the PD with the central MQW LED in the on and off states are provided in the upper and lower parts, respectively. The illumination of the central MQW LED only increases the DC bias and has little influence on the signal and noise amplitudes of the output voltage. Moreover, the PD response rate can reach 500 bps while higher rates would result in severe distortions. However, as the heart rate is usually several Hertz, the PD of the integrated optoelectronic chip guarantees sufficient resolution of heartbeat waveforms.

The ring-structured integrated optoelectronic chips are used to detect a PPG pulse signal that contains small AC and large DC components. The AC or pulsatile components are due to the reflected light and are related to blood volume changes that result in attenuation variability in the incident light, as shown in Figs. 7(a) and 7(b). The DC or steady components are due to the light emitted directly from the LED and that reflected and scattered from the arterial, venous, and tissue layers. Figures 7(c) and 7(d) demonstrate the PD current waveform with the packaged green integrated optoelectronic chips placed on a fingertip and wrist, respectively. The PD currents are measured using an Agilent Technologies B1500A semiconductor device analyzer with a 20 mA current applied to the LED. The results indicate that the amplitude of the PPG pulse signal collected from the fingertip is greater than that from the wrist. The results from the blue integrated optoelectronic chips shown in Figs. 7(e) and 7(f) exhibit the same trend. Furthermore, the amplitude of the PPG pulse signal based on the green integrated optoelectronic chip is significantly weaker than that of the blue chip. Therefore, the blue chip is selected to constitute the complete PPG pulse sensor prototype. A schematic diagram of the sensor system is shown in Fig. 7(g), which consists of an integrated optoelectronic chip with a novel ring structure, amplifier and filter circuits for week signal processing, signal analysis and display units based on an Arduino board. The blue integrated optoelectronic chip and the week signal processing circuits are packaged in a finger-sized PCB. The processed PPG pulse signal collected from the

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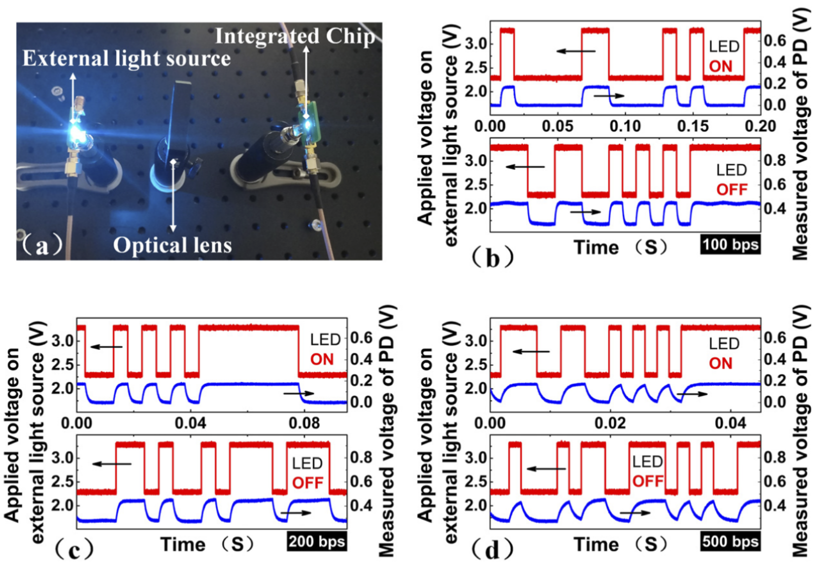

Fig. 6. (a) Test platform to verify the PD's ability to detect external modulated optical signals, measured voltage of the PD under an incident PRBS data rate of (b) 100, (c) 200, and (d) 500 bps.

fingertip is illustrated in Fig. 7(h), and the corresponding heartbeat can be obtained from the software algorithm. Therefore, the proposed PPG pulse sensor can realize real-time heart pulse monitoring.

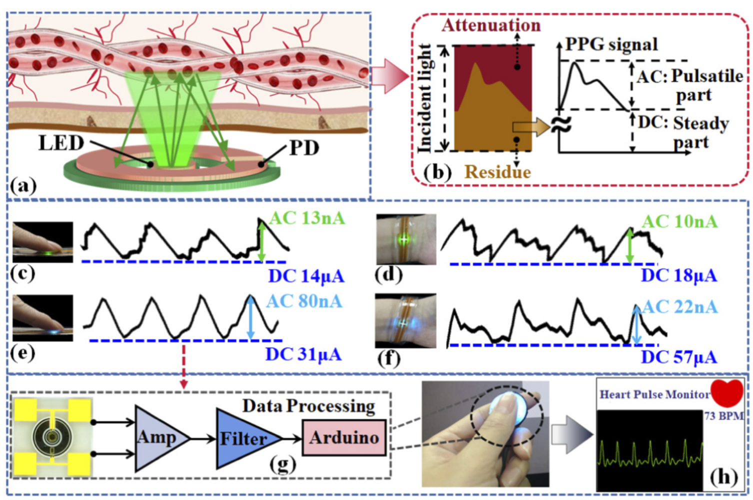

Fig. 7. (a) Working principle of the reflection-type PPG pulse sensor, (b) typical PPG pulse signal that contains AC and DC components, PD current waveform with the packaged green integrated optoelectronic chip placed on (c) a fingertip and (d) wrist, PD current waveform with the packaged blue integrated optoelectronic chips placed on a (e) fingertip, and (f) wrist, (g) schematic diagram of the sensor system, and (h) processed PPG pulse signal collected from a fingertip using the blue integrated optoelectronic chip.

4. Conclusions

In this work, ring-structured integrated optoelectronic chips as used for reflection-type PPG pulse sensor were fully characterized. The suitable LED epitaxial wafer and the measurement position on human skin were determined. A reflector was used to simulate human skin, and the results indicate that the distance between the chip and human skin should be as small as possible. Furthermore, the response rate of the PD in the integrated optoelectronic chips can reach 500 bps, which is sufficient for the PPG pulse sensor. For higher sensitivities, larger chips are preferred at the expense of the response rate. The reflection-type PPG pulse sensor prototype based on a blue integrated optoelectronic chip successfully realized real-time heart pulse monitoring and is important in daily health nursing.

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Data availability. No data were generated or analyzed in the presented research.

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